SEARCHES FOR NEW PHENOMENA AT COLLIDERS

E. PEREZ

CE-Saclay, DSM/DAPNIA/Spp, F-91191 Gif-sur-Yvette, France

E-mail: eperez@hep.saclay.cea.fr

An overview of recent experimental results on searches for new phenomena at the LEP, HERA and Tevatron high energy colliders is presented, including in particular new results obtained from the analysis of the Run II data at the Tevatron. No significant evidence for physics beyond the Standard Model has been found and limits at the 95% confidence level have been set on the mass and couplings of several new particles. The complementarity between the different experiments is discussed, as well as future prospects for ongoing and future experiments.

1. Introduction

Although remarkably confirmed by low and high energy experiments over the last 30 years, the Standard Model (SM) of strong, weak and electromagnetic interactions remains unsatisfactory and incomplete. Due to the huge hierarchy between the electroweak and the Planck scales, breaking the electroweak symmetry spontaneously via a fundamental scalar field imposes an extreme fine-tuning of the mass of the latter field. One of the most popular solutions to that problem is brought by Supersymmetry (SUSY), which allows some cancellation between the loop corrections responsible for that fine-tuning.[a] Alternative solutions may be obtained by breaking the electroweak symmetry in a dynamical way, or by extending the space-time by additional space dimensions.

In addition, there are many questions which are not answered by the SM or its simplest supersymmetric extensions. For example, the SM does not explain the quantization of the electromagnetic charge, or the observed "replication" of three fermion families. It does not explain either the origin of fermion masses or the observed hierarchy between them. Many models of "new physics" have been proposed to address these issues.

Experimentally, new physics might manifest itself in rare meson decays, in precision measurements, in the search for Lepton Flavor Violating processes such as the $\mu \to e\gamma$ conversion, in the search for Cold Dark Matter, etc.. High energy colliders also provide a very high sensitivity to new phenomena, allowing new massive particles to be directly looked for, or the effect of new interactions interfering with known SM processes to be studied.

The LEP (Large Electron Positron) collider ran until end 2000 at a centre-of-mass energy $\sqrt{s}$ up to 209 GeV, and delivered about 1 fb^{-1} to the ALEPH, DELPHI, L3 and OPAL experiments. Extensive searches for new phenomena have been carried out and the final analyses are being completed. Stringent constraints have been set especially on new particles coupling preferably to the electroweak bosons.

The Tevatron proton-antiproton collider delivers data to the D0 and CDF experiments. During the first phase ("Run I") which ended in 1996, both experiments collected about 120 pb^{-1} of luminosity. The Tevatron has restarted in May 2001 with a larger centre-of-mass energy of 2 TeV. The increased energy, the improved detector capabilities, and the much larger expected luminosities of several fb^{-1} provide a large discovery potential for new phenomena. About 300 pb^{-1} has been delivered so far, with more than 200 pb^{-1} collected by the experiments with fully operational detectors. The Run II results presented in the following were obtained with a luminosity of about $100 - 130$ pb^{-1}.

At HERA (Hadron Electron Ring Accelerator), electrons (or positrons) collide with protons at $\sqrt{s} \simeq$ 320 GeV. During the first phase of data taking which ended in mid-2000, the two colliding experiments H1 and ZEUS collected about 120 pb^{-1} of luminosity. The restart of HERA in the fall of 2001 has been more difficult than expected, but the machine should now be able to deliver again high luminosities. Besides its lower energy and the limited possibility to produce new particles by pair, HERA appears very well suited to look for particles coupling to an electron and a first generation quark, or to search for new phenomena for which the SM backgrounds at the Tevatron are not easy to handle.

[a] An overview of experimental results on searches for Supersymmetry is given elsewhere in these proceedings.[1]

2. Any Hints for New Physics?

The most convincing evidence so far for physics beyond the Standard Model is the observation that neutrinos oscillate.[2] However, the SM can easily accomodate neutrino masses and the current observations do not provide a strong guidance to which kind of new physics should extend the SM.

On the other hand, some precision measurements deviate slightly from the corresponding SM expectations[b] and some "interesting" events have been observed at high energy colliders. In the next section I shortly review some of these observations which, if confirmed, might provide hints for new physics.

2.1. *Precision Measurements*

In atomic physics, the interference of photon and Z exchange between the valence electron and the nucleus leads to transitions which would be forbidden by QED alone. Such transitions allow one to measure a (small) parity violating asymmetry giving access to the so-called weak charge, which might be affected by the exchange of new particles, such as new Z bosons or leptoquark bosons. The weak charge has been measured to 0.6% in Cesium atoms.[4] Until spring 2003, this measurement showed a discrepancy of more than 2σ with the SM prediction. The latter has been revisited recently[5] and the new calculation agrees very well with the experimental value.

The precise measurement of the anomalous magnetic moment of the muon is known to be very sensitive to new physics effects, such as loops induced by sleptons and charginos in supersymmetric theories. The experimental world average, largely dominated by the measurement done by the $(g-2)_\mu$ Collaboration at BNL, reaches the impressive precision of 0.7 ppm. On the other hand, the theoretical expectation still suffers from uncertainties related to the evaluation of the hadronic vacuum polarization. This can be estimated by using either hadronic cross section measurements done in low energy e^+e^- collisions, or the spectral functions of hadronic tau decays. In the latter case, the resulting SM prediction for $(g-2)_\mu$ agrees well with the measurement, while some discrepancy exists when using low energy e^+e^- data.[6] The CMD-2 Collaboration revisited its $\pi\pi$ cross sections recently.[7] Taking into account these new measurements, the discrepancy remains of the order of 2σ.

At the ICHEP'02 conference, both the BaBar and BELLE Collaborations reported a discrepancy between the measurements of $\sin 2\beta$ in the $B \to J/\psi K_s$ and $B \to \Phi K_s$ modes, with the combined effect being at the level of 2.7σ. Updated results were presented at this symposium[8] and the BELLE experiment confirms this deviation. This observation has already triggered quite some speculations, although it does not seem easy for some "new physics" to account for it, without contradicting measurements on the $b \to s\gamma$ decay or on the B_d mixing parameter.

2.2. *Tevatron Events with Lepton(s) and Photon(s)*

In 1995, the CDF experiment observed a spectacular event with two electrons, two photons, and a large amount of missing transverse energy in the final state.[9] Due to the very low expectation for such events within the SM, this triggered a lot of activity and in particular revived somehow the supersymmetric models where SUSY breaking is mediated by gauge interactions. Both the D0 and CDF experiments looked for such events in a sample of about 100 pb^{-1} of Run II data, and no new candidate has been observed. One can note that with their improved hermiticity, the Run II detectors are very well suited to study such final states.

The CDF data from Run I also showed a slight excess of events with a lepton and a photon, both at high transverse momentum P_T, together with some large missing transverse energy.[10] This excess is not confirmed in the data from Run II, and the current CDF measurement of $W\gamma$ production shows a very good agreement with the SM expectation.

2.3. *The "Superjets" Observed at CDF Run I*

In the data from Run I, the CDF experiment reported an excess of events with 2 or 3 jets and a W boson, where one of the jets was emerging from a secondary vertex and also contained a soft lepton (such jets, doubly identified as b candidates, were called "superjets").[11] The experiment observed 13 such events for a SM expectation of 4.4 ± 0.6. These events were seen to have atypical kinematic proper-

[b] A detailed review of precision measurements including topics not discussed here can be found elsewhere.[3]

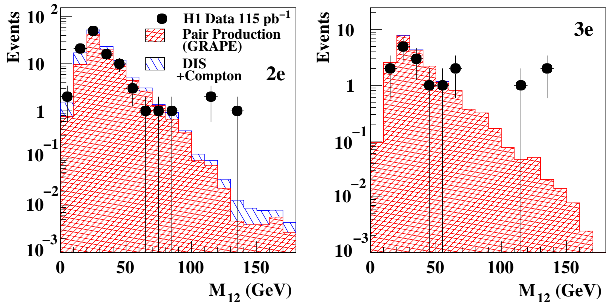

Figure 1. Distribution of the invariant mass of the two highest P_T electrons in events with (left) exactly two and (right) exactly three measured electrons. The H1 data (symbols) are compared with the prediction from the SM, dominated by two photon processes.

ties and many checks were performed to try to understand them, which did not show any experimental bias. So far, there is no statement from Run II data on such events. Work is going on in both D0 and CDF experiments to study the correlations between various b-tagging algorithms.

2.4. *HERA Multilepton Events*

The H1 Collaboration recently published the first measurement of multilepton production cross section in ep collisions.[12] At HERA multilepton events are mainly produced via $\gamma\gamma$ collisions, with the incoming electron being often scattered at very small angles and thus undetected. Figure 1 shows the distribution of the invariant mass M_{12} of the two highest P_T electrons, for final states with (left) exactly two and (right) exactly three measured electrons.[c] The data are well described by the SM expectation besides at largest masses. For $M_{12} > 100$ GeV, 6 events are observed for a SM expectation of 0.53 ± 0.06. On the other hand, a preliminary analysis of the ZEUS data[13] does not show any significant excess.

2.5. *HERA Events with a Lepton and Large Missing Transverse Energy*

In 1994, the H1 Collaboration reported the observation of an $e^+p \rightarrow \mu^+X$ event with high transverse momenta. Since then, other similar events with a high P_T isolated lepton, a large amount of missing transverse energy, and a high P_T hadronic final state have been observed in the H1 data[14] and the study of such final states has been of highest interest in both the H1 and ZEUS Collaborations. The main SM contribution to such final states comes from W production, for which the cross section at HERA is about 1 pb. Although the events observed in H1 look compatible with the W hypothesis, Fig. 2 shows that an excess of events is observed in the data for high values of the transverse momentum P_T^X of the hadronic final state. For $P_T^X > 25$ GeV, 10 events are observed where the isolated lepton is a muon or an electron, for a SM expectation of 2.92 ± 0.49. For $P_T^X > 40$ GeV 6 events are still observed while the SM expectation is 1.08 ± 0.22. The ZEUS experiment does not observe a significant excess of events with the lepton being an electron or a muon, but reports the observation of 2 events at $P_T^X > 25$ GeV with a τ lepton decaying hadronically.[15] That is in slight excess of the SM expectation of 0.12 ± 0.02 event.

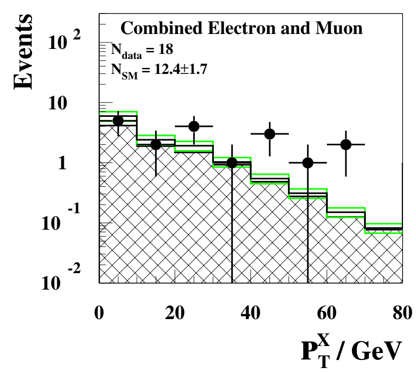

Figure 2. Distribution of the transverse momentum of the hadronic final state for events with a high P_T isolated e or μ and missing transverse energy. The H1 data (symbols) are compared with the SM expectation, dominated by W production (hatched histogram).

2.6. *Comments on the Above Observations*

The excesses reported in the three previous paragraphs are clearly statistically limited. We are looking forward to seeing new results on events with "superjets" in the Tevatron experiments. H1 should be able to clarify the two excesses observed with the much larger luminosities expected within the next years. Meanwhile, assuming that the "anomalies" seen at H1 are a sign for some new physics, one may wonder whether something should also have been seen by the LEP and Tevatron experiments. New physics in ep collisions might proceed via a lepton-quark interaction, or via $e\gamma$ or γp collisions.

[c] "Electron" actually stands here for e^- and e^+.

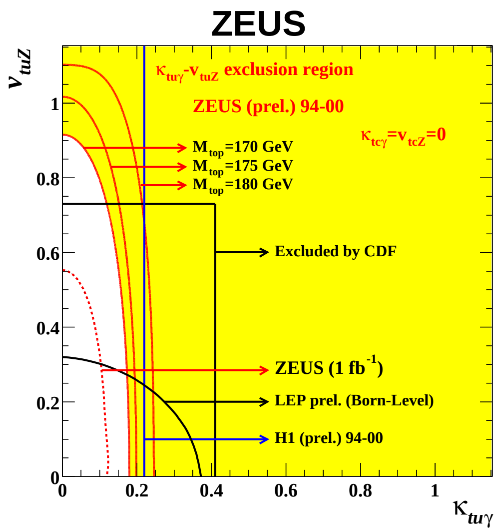

Figure 3. Existing constraints on the anomalous FCNC magnetic (vectorial) coupling of a top quark to a u quark and a photon (a Z) derived from the HERA, Tevatron and LEP experiments. The expected sensitivity of HERA experiments with 1 fb^{-1} is also shown as the dashed curve.

The first case would have very model dependent consequences at other colliders. The "partonic" $e\gamma$ (γq) luminosities are much larger at LEP II (Tevatron) than at HERA. Thus it is likely that any new physics proceeding via $e\gamma$ (γq) collisions would have a much larger cross section at LEP II (Tevatron). On the other hand the corresponding SM backgrounds should also be much larger. This may make the signal very difficult to single out from the background.

An example of that is provided by the "anomalous single top" interpretation of the events reported in Sec. 2.5. Anomalous couplings between a light quark (u or c), a gauge boson and a top quark are present in several extensions of the SM. These might allow for single top production at LEP and at HERA (which, otherwise, has a tiny cross section in the SM); for an enhanced single top production rate at the Tevatron; for rare decays $t \rightarrow q\gamma(Z)$. Amongst the events reported in Sec. 2.5, 5 candidates fulfil dedicated criteria designed to select single top events, while the SM expectation is 1.31 ± 0.22. No significant excess is observed in the hadronic channel. Using the convention given in,[16] an anomalous coupling $\kappa_{tu\gamma}$ of $0.20^{+0.05}_{-0.06}$ would be needed to account for these observations.[17] As shown in Fig. 3 this range of coupling values is not yet ruled out by other experiments.[18−20]

At the Tevatron, the anomalous single top production cross section induced by a $\kappa_{tu\gamma}$ coupling could be quite large, e.g. about 2 pb for $\kappa_{tu\gamma} = 0.2$. However this rate is similar to that of SM single top production, the observation of which is challenging due to the huge W+jets background.[d] As a result, the future sensitivity on $\kappa_{tu\gamma}$ of the Tevatron experiments with a luminosity of 2 fb^{-1} will remain driven by the study of decays $t \rightarrow q\gamma$. It should reach about 0.1, similar to the expected sensitivity of HERA experiments with a luminosity of 1 fb^{-1}.

3. Searches for New Resonances

3.1. *Excited Fermions*

The observed replication of three fermion families motivates the possibility of a new scale of matter yet unobserved. Deep-inelastic scattering (DIS) experiments have been known for a long time to be very well suited to study the structure of hadronic matter.[e] At HERA, where the exchanged boson probes the proton with a resolution corresponding to scales up to 10^5 GeV^2, a finite quark radius would reduce the DIS cross section compared to its SM values, this effect being more prominent when the square of the four-momentum carried by the gauge boson (Q^2) is large. The study of the full statistics of high Q^2 DIS data allowed both the H1 and ZEUS experiments[23] to rule out quark radii smaller than about 10^{-18} m, assuming the electron to be point-like.

Besides these indirect effects, an unambiguous signature for a new scale of matter would be the direct observation of excited states of fermions (f^*), via their decay into a gauge boson. Effective models describing the interactions of excited fermions with standard matter have been proposed.[24−26] In the most commonly used model,[24,25] the interaction of an f^* with a gauge boson is described by a magnetic coupling (i.e. a dimension-five operator) proportional to $1/\Lambda$ where Λ is a new scale. Proportionality constants f, f' and f_s result in different couplings to $U(1)$, $SU(2)$ and $SU(3)$ gauge bosons. Existing constraints on excited electrons are shown in Fig. 4, under the assumption that $f = f'$. Searches for pair produced e^* at LEP[27] allowed masses below

[d] At Run I, only an upper bound of about 15 pb could be set on the cross section of that process.[21]

[e] More generally two fermion production processes are sensitive probes to fermion compositeness.[22]

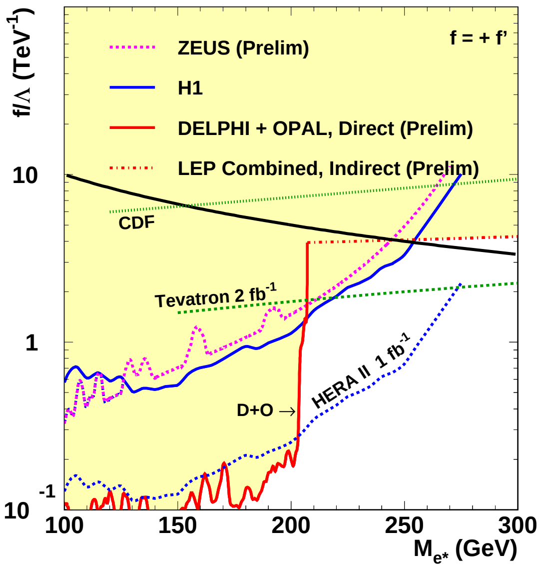

Figure 4. Existing constraints on excited electron masses and couplings, assuming that $f = f'$. The decreasing curve shows the hyperbola $f/\Lambda = 1/M_{e^*}$. The uppermost dotted line shows the translation of the CDF Run II constraint coming from single e^* search. Also shown as dotted curves are the future sensitivities of HERA and Tevatron experiments.

about 103 GeV to be ruled out, independently of the value of the coupling f/Λ. In contrast, searches for single e^* production at LEP[28] and at HERA[29] set mass bounds which depend on f/Λ. The best sensitivity at highest masses is provided by looking for indirect effects in $e^+e^- \to \gamma\gamma$ which might be induced by e^* t-channel exchange.[30]

Recently, the CDF experiment looked for the single production of an excited electron focusing on the decay $e^* \to e\gamma$. In the formalism of Baur *et al.*,[26] which differs from that used by others[24,25] mainly by a different normalization, e^* masses M_{e^*} up to 863 GeV can be ruled out assuming $\Lambda = M_{e^*}$. My interpretation of this constraint in the model of[24,25] is shown in Fig. 4 as the upper dashed-dotted curve. Also shown in Fig. 4 are the future sensitivities of HERA and Tevatron. Although e^* have been severely constrained at LEP, a much larger discovery potential remains at the Tevatron for other generations of excited leptons.

3.2. *Dijet Resonances*

The Tevatron is very well suited to look for excited quarks and other new particles coupling strongly to quarks or gluons, which might manifest themselves as dijet resonances. With a resolution of about 10% of the dijet mass, CDF looked for narrow resonances in the dijet spectrum measured in the data from Run II. No signal was observed and mass bounds were derived for several new particles, as shown in Fig. 5. In particular, the data allow to exclude axigluons and (color universal) colorons[31] with masses below 1130 GeV, under the assumption that the coupling of these new colored bosons to a $q\bar{q}$ pair is the standard strong coupling. This is the first direct mass bound above 1 TeV obtained so far.

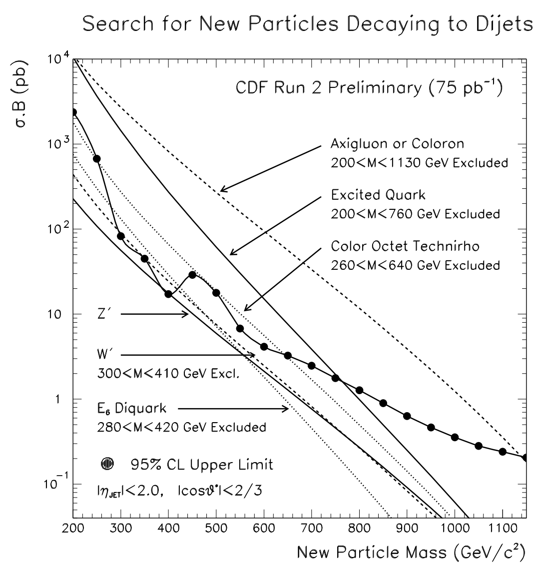

Figure 5. Mass dependent upper bound on the production cross section of a resonance times the branching ratio of its decay into two jets. The experimental constraint (symbols) is compared to the prediction of several models allowing lower mass bounds to be set on the new resonances they predict.

3.3. *Leptoquarks*

An intriguing characteristic of the Standard Model is the observed symmetry between the lepton and the quark sectors, which is manifest in the representation of the fermion fields under the SM gauge groups, and in their replication over three family generations. This could be a possible indication of a new symmetry between the lepton and quark sectors, leading to "lepto-quark" interactions. Leptoquarks (LQs) are new scalar or vector color-triplet bosons, carrying a fractional electromagnetic charge and both a baryon and a lepton number. Several types of LQs might exist, differing in their quantum numbers. A classification of LQs has been proposed by Buchmüller, Rückl and Wyler (BRW)[32] under the assumptions that LQs have pure chiral couplings to SM fermions, and that a given LQ couples only to fermions of a given family. The interaction of the LQ with a lepton-quark pair is of Yukawa or vector nature and is parameterized by a coupling λ. Assuming that LQs belonging to the same isospin multiplet are mass degenerate, the LQ decays only into a quark and a neutrino or a charged lepton, and the branching ratio β of the latter decay mode is 1 or 1/2.

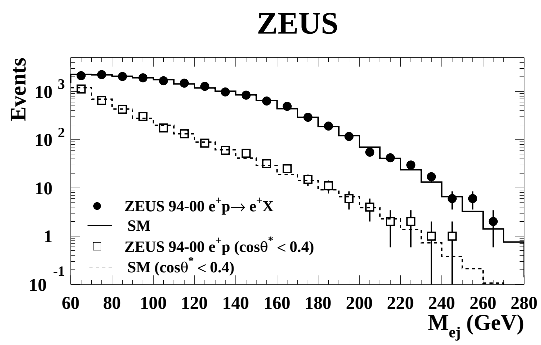

Figure 6. Distribution of the electron-jet invariant mass for high Q^2 Neutral Current DIS candidate events. The ZEUS data (symbols) are compared with the SM prediction (histograms), before and after applying an angular cut designed to maximize the sensitivity to a scalar LQ signal.

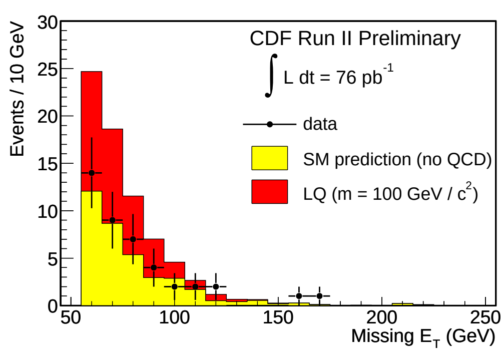

Figure 7. Distribution of the missing transverse energy measured by the CDF experiment for events with at least two hard jets. The additional expected contribution of pair produced scalar leptoquarks with mass 100 GeV is also shown as the dark histogram.

In electron-proton collisions, first generation LQs might be singly produced via the fusion of the incoming lepton with a quark coming from the proton. Hence they might be observed as a resonant peak in the distribution of the lepton-jet mass spectrum of Neutral or Charged Current DIS events. No such signal has been observed by the H1 and ZEUS experiments. As an example, Fig. 6 shows the invariant mass distribution of Neutral Current DIS events measured in the ZEUS data,[33] which agrees well with the SM expectation up to the highest masses.

At the Tevatron, leptoquarks are mainly pair produced via their coupling to gluons. First generation LQs have been looked for in Run II data in the $eejj$, $e\nu jj$ and $\nu\nu jj$ final states, with the letter j denoting generically a jet. In the first two cases, a large amount of SM backgroud comes from QCD events where a jet "fakes" an electron and has to be determined from the data. Searching for the signal in the last two channels requires a good understanding of the measurement of missing transverse energy. Figure 7 shows that indeed the distribution of missing transverse energy is well controlled.

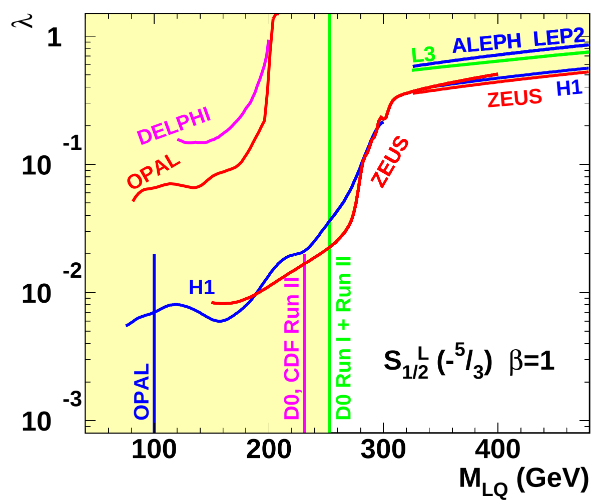

Figure 8. Example mass-dependent upper bounds on the Yukawa coupling λ of a first generation leptoquark to the electron-quark pair. These are shown for a scalar LQ which decays exclusively into an electron and a quark.

Existing constraints on a scalar leptoquark which decays solely into an electron and a quark are summarized in Fig. 8. For an electromagnetic strength of the coupling λ ($\lambda^2/4\pi = \alpha_{em}$), HERA experiments[33,34] rule out LQ masses below $\sim$ 290 GeV. Constraints on high mass LQs were also obtained by the LEP experiments, where the $t-$channel LQ exchange might affect the observed cross section for the process $e^+e^- \to q\bar{q}$. In contrast, constraints derived from the search for pair produced LQs at the Tevatron do not depend on the coupling

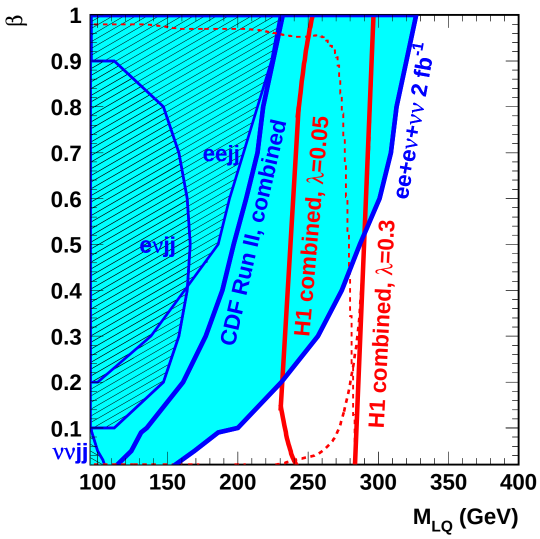

Figure 9. Example constraints on first generation scalar leptoquarks decaying exclusively into eq and νq. For $\lambda = 0.3$, the H1 constraints obtained from the ej and νj analyses are indicated by the dashed curves, and the combined bound is shown for two values of the coupling. Also shown is the future sensitivity of the Tevatron for a luminosity of 2 fb^{-1}.

λ. By combining data from Run I[35] and Run II, D0 rules out LQ masses below 253 GeV, which is the most stringent bound existing so far on scalar LQs decaying only into an electron and a quark.

Relaxing some of the BRW assumptions, more general LQ models might be constructed where the branching ratio β for the LQ to decay into an electron and a quark is a free parameter of the model.[f] Example constraints on such LQ models are shown in Fig. 9 assuming that the LQ decays exclusively into eq and νq. Leptoquarks decaying with a large branching ratio into νq are not easily probed at the Tevatron due to the large background. HERA experiments can provide a better sensitivity in such cases if the Yukawa coupling λ is reasonably large.

Leptoquarks coupling to second or third generation fermions and with masses above 100 GeV can be directly searched for only at the Tevatron. Pair produced LQs leading to final states with two muons and two jets have been searched for in the Run II data by the D0 experiment. The resulting mass bound of 186 GeV is close to that obtained with Run I data using a much more involved analysis.[36]

[f] An example of such LQs is provided by supersymmetric partners of quarks possessing R-parity violating couplings to a lepton-quark pair.

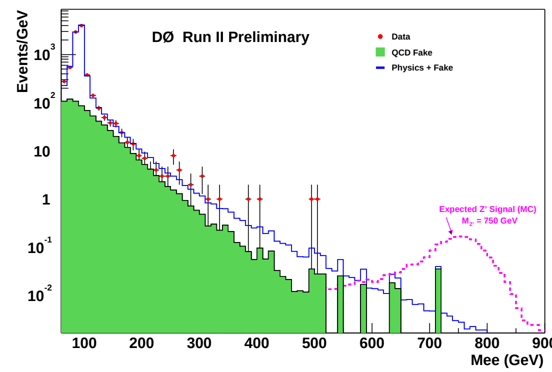

Figure 10. Distribution of the dielectron invariant mass observed by the D0 experiment. Above the Z peak, a large contribution to the SM expectation (white histogram) comes from QCD processes where a jet "fakes" an electron (shaded histogram).

3.4. *Searches for New Gauge Bosons*

New resonances coupling to leptons are predicted in several extensions of the Standard Model. Extending the gauge group of the SM often leads to additional Z' bosons, with most popular models being left-right symmetric or based on the E_6 Grand Unification group.

Both the D0 and CDF experiments looked for such dilepton resonances[g] in the data from Run II. As an example, Fig. 10 shows the dielectron invariant mass distribution measured by the D0 experiment. The measurement agrees well with the SM prediction up to the highest masses. A similar agreement is observed in the dimuon channel. Combining the dielectron and dimuon channels bounds on the Z' mass have been obtained in several models, some of which are shown in Fig. 11.

They range between 545 and 730 GeV, with the most stringent bound obtained in the "Sequential Standard Model" where the new Z' boson couples to fermions in the same way as the standard Z. In that case however, indirect bounds coming from the measurements of cross sections and forward-backward asymetries at LEP provide stronger constraints. In contrast, in the E_6 inspired types of models, the direct bounds obtained at the Tevatron are the most stringent and less dependent on the model parameters. While the ultimate sensitivity of the Tevatron experiments should approach 1 TeV, the LHC will be able to probe Z' masses up to $4-5$ TeV.

[g] As shown in Fig. 5, the search for a new boson in the dijet channel has a limited sensitivity.

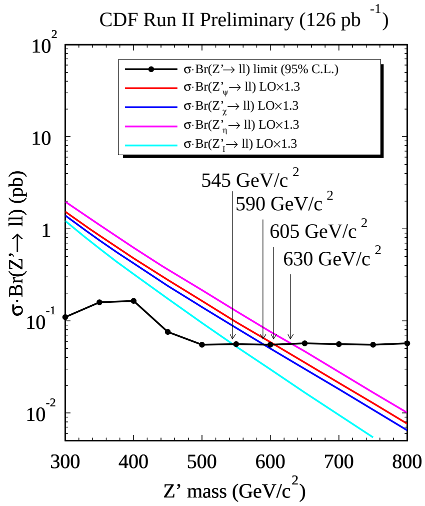

Figure 11. Upper bounds on the production cross section of a new Z' boson times its branching ratio to decay into a dilepton pair. Both the ee and $\mu\mu$ channels are combined. Resulting bounds in several E_6-inspired Z' models are also shown.

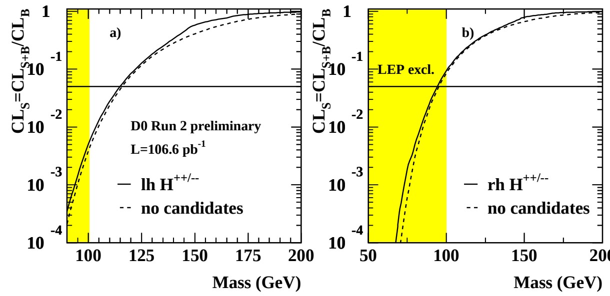

Figure 12. Confidence level of the doubly-charged Higgs hypothesis as a function of the $H^{\pm\pm}$ mass, as obtained from the D0 search for pair-produced $H^{\pm\pm}$ decaying into muons.

3.5. *Doubly-charged Higgses*

In addition to dilepton resonances possessing no net lepton number, new particles coupling to two leptons of the same charge might also be considered. Such particles are predicted in models with an exotic extended Higgs sector, such as left-right symmetric models where the symmetry $SU(2)_L \times SU(2)_R$ is broken by a triplet of $Y = 2$ scalar fields, containing a doubly-charged Higgs field.[37] Such models might naturally provide (small) Majorana mass terms for the neutrinos. The pair production of doubly-charged Higgses has been looked for by DELPHI and OPAL,[38] considering all possible dilepton decay modes for the $H^{\pm\pm}$. This yields mass limits of about 100 GeV. Doubly-charged Higgses might also be singly produced at LEP and HERA[39] via the process $e^{\pm}\gamma \to e^{-}H^{\pm\pm}$. In that case, the production cross section depends, in addition to the $H^{\pm\pm}$ mass, on its unknown coupling h_{ee} to a dielectron pair.[h] A dedicated analysis of the H1 events described in Sec. 2.4 does not support the $H^{\pm\pm}$ hypothesis for these events.[40] This is confirmed by the search for singly produced charged Higgses carried out by OPAL,[41] which sets strong bounds on the single $H^{\pm\pm}$ production cross section in $e\gamma$ collisions.

Pair production of doubly charged Higgses has also been looked for at the Tevatron experiments using the data from Run II. CDF searched for a signal in the $e^-e^-e^+e^+$ final state. Although no mass bound could be set with the current statistics, the future sensitivity should reach about 180 GeV. In contrast, doubly-charged Higgses coupling to muons are already constrained by the Tevatron. As shown in Fig 12, masses below 116 (95) GeV can be ruled out for $H^{\pm\pm}$ coupling to left- (right-) handed muons.

3.6. *Resonant Kaluza-Klein Gravitons*

The phenomenological and experimental interest in higher-dimensional physics has been considerably renewed recently, after it was realized that compactified extra dimensions could yield observable effects at the current or foreseen experiments. Models with extra space dimensions try to address the problem of the huge hierarchy between the Planck and the electroweak scales. The experimental constraints on models with "large" extra dimensions, resulting in a "strong" gravity at the TeV scale, will be reviewed in Sec. 4. This paragraph considers the case of "small" extra dimensions, where the gravity is "localized" on a brane, apart from another brane where the SM fields are confined. The propagation of gravity in the extra dimension is exponentially damped due to a fine-tuned space-time metric as proposed by Randall and Sundrum,[42] resulting in the weakness of gravity when observed from the SM brane.

Since it propagates in the extra dimension, the graviton observed in $4d$ manifests itself as a "tower" of Kaluza-Klein (KK) modes, with the zeroth mode corresponding to the massless graviton. In models of localized gravity the first graviton excitation $G^{(1)}$ is

[h] Note that this Yukawa coupling is not expected to be vanishingly small since the Higgs triplet is not involved in the generation of fermion Dirac mass terms.

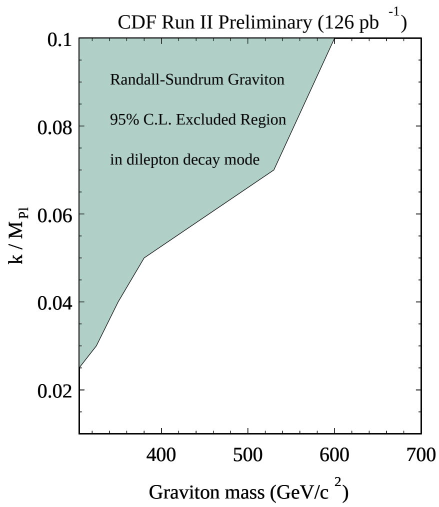

Figure 13. Constraints set on Kaluza-Klein graviton mass and coupling obtained by combining the ee and $\mu\mu$ channels.

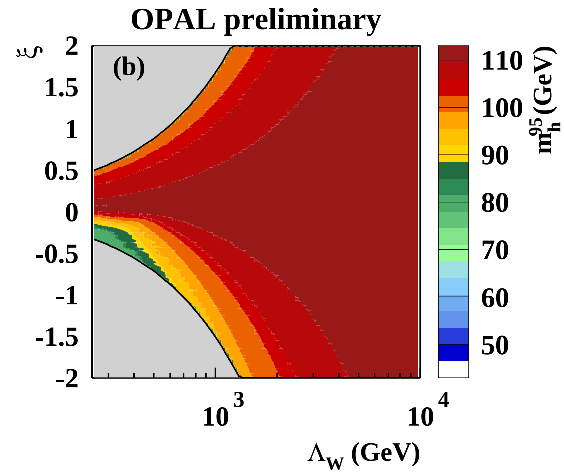

Figure 14. Lower limits on the mass of the Higgs-like scalar field as a function of the mixing parameter ξ between the Higgs and the radion and of the scale parameter Λ_W corresponding to the vacuum expectation value of the radion.

expected to be heavy, with a mass around the TeV scale. Its coupling to SM particles is determined by a model parameter (k/M_{Pl}) and is expected to be sizeable. Hence, resonant production of $G^{(1)}$ might be observed at the Tevatron or future colliders. Using the data from Run II, the CDF experiment looked for such a signal when the $G^{(1)}$ decays hadronically or leptonically into ee or $\mu\mu$, with the latter modes providing the largest sensitivity. Resulting bounds are shown in Fig. 13. These are the first direct constraints on Randall-Sundrum models.

3.7. *Searches for Radions*

In models with extra dimensions the excitations of the metric tensor along the new coordinates yield new scalar fields. In the simplest version of the Randall-Sundrum model with five dimensions there is only one such scalar field. For each mode k its k^{th} Kaluza-Klein excitation is "eaten" to provide the additional degrees of freedom to the massive $G^{(k)}$, such that only the zeroth mode, the so-called "radion", remains.[43,44] The radion might mix with the SM Higgs boson.[44] Since the radion couples strongly to gluons the lightest scalar field resulting from this mixing may have dominant decay modes which differ from those of the SM Higgs. The OPAL experiment reinterpreted its flavor-independent Higgs searches to set first constraints on such models.[45] An example of those is shown in Fig. 14.

4. Effects of Additional Large Space Dimensions

The phenomenology of models with large extra dimensions[46,47,43] is widely different from that of Randall-Sundrum models. Here, the weakness of gravity in the $4d$ world can be accounted for by the "dilution" of gravity flux lines in large extra dimensions. The fundamental scale characterizing the gravity in the full space, M_D, might be of the order of the TeV for a compactification radius of the extra dimensions up to about 0.1 mm. Such large radii are actually not ruled out by experiments measuring gravity at submillimeter distances.

4.1. *Direct Searches for KK Gravitons*

In these models the Kaluza-Klein excitations of gravitons form a quasi continuum in mass. Hence, although the coupling of $G^{(k)}$ to SM fields is tiny, the production cross section of Kaluza-Klein gravitons might be large due to the huge multiplicity of accessible states. Once produced a $G^{(k)}$ would escape detection because of its very small coupling such that the typical signature of graviton production is the presence of missing energy. Most sensitive direct bounds come from the LEP experiments which searched for $e^+e^- \to \gamma G^{(k)}$. The L3 experiment[48] rules out M_D values lower than 1.5 TeV (0.9 TeV) in the case of $n = 2$ (4) extra dimensions. At hadronic colliders, final states with a jet and missing energy are the most sensitive channels to directly search for KK gravitons. Data from the Run I of the Tevatron[49] allowed to set a lower bound of about 1 TeV on M_D, while the LHC experiments with 100 fb^{-1} should reach a sensitivity of 7 to 8 TeV.[47]

4.2. *Indirect Effects of KK Graviton Exchange*

Another way to search for large extra dimensions is to look for the effect of graviton exchange and its interference with SM processes. Calculations need to be performed by introducing an effective coupling λ/M_s^4, where the parameter λ is expected to be close to one and the effective scale M_s should not differ too much from the fundamental scale M_D.[i] Several formalisms have been proposed for this effective coupling.[47−51] Bounds given below use the convention of Giudice *et al.*.[47] Combining all LEP data on Bhabha scattering and $\gamma\gamma$ production, a lower bound on M_s of 1.35 TeV can be set.[52] The study of NC DIS at HERA rules out M_s values below 0.82 TeV.[23] The D0 experiment searched for indirect effects induced by KK graviton exchange in the ee, $\gamma\gamma$ and, for the first time, in the $\mu\mu$ final states. Figure 15 shows the dimuon invariant mass measured by D0 together with the effect of additional contribution of graviton exchange for several values of M_s. Combining the ee and $\gamma\gamma$ analyses from Run I[53] and Run II, the constraint $M_s > 1.38$ TeV is obtained, which is the most stringent bound so far.

4.3. *Searches for Branons*

The assumption that the brane on which the SM fields are confined is allowed to "vibrate" in the extra dimensions might modify the phenomenology of extra dimensional models.[54] A small brane tension would result in a large suppression of the production rate of $G^{(k)}$ for high modes (large $|k|$), such that the "standard" signal of direct graviton production might not be observable. The counterpart is that the scalar fields associated to the brane vibration, called "branons", might in turn be produced with a sizeable rate. The experimental signature would remain the same as for graviton production, i.e. missing energy.

[i]Indirect effects induced by graviton exchanges thus allow to probe the scale M_s but do not provide a direct probe of M_D.

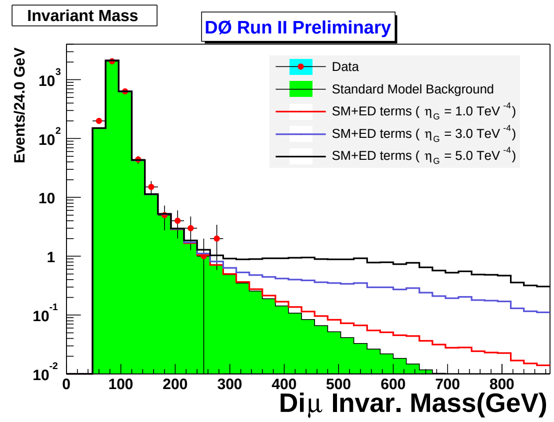

Figure 15. Distribution of the dimuon invariant mass measured by the D0 experiment. The data (symbols) are compared to the SM expectation (shaded histogram). Several examples of the deviation from the SM prediction induced by Kaluza-Klein graviton exchange are also shown.

A re-interpretation of the $\gamma + E_{missing}$ analysis has been performed by L3[55] to set some bounds on the branon mass depending on the brane tension. These are shown in Fig. 16. For very elastic branes, $f \to 0$, branons with a mass below 103 GeV are ruled out.

5. Model-independent Searches

The searches for new phenomena reported in the previous sections are driven by specific models: within a given model, the analysis is optimized in order to maximize the sensitivity to the "known" signal. Many models are investigated by experiments, and models themselves actually offer quite some freedom via their free parameters. However, additional information can be brought by a complementary approach consisting in a broad-range search for deviations from the SM prediction. Such an approach should consider phase space regions where the SM prediction is sufficiently reliable, e.g. those where the particles in the final state have a large transverse momentum.

This approach has been pioneered by the D0 Collaboration using the full statistics of Run I data.[56] It has been recently applied to the full sample of data collected by H1.[57] The strategy begins with definition criteria for "objects", as electrons, muons, photons, jets, W/Z, or neutrinos. Channels are then defined as final states with at least two objects, and the data are compared to the SM expectation in each channel. For example, Fig. 17 shows that an overall good agreement is observed in all channels considered in

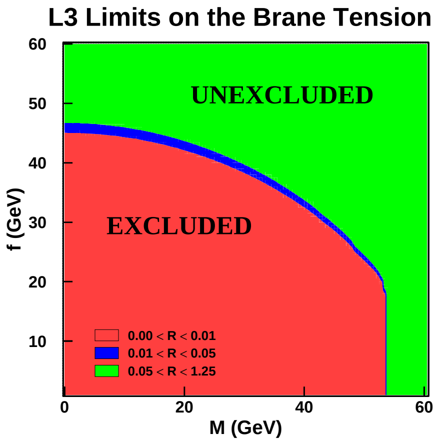

Figure 16. Constraints on the branon mass as a function of the brane tension, obtained from the analysis of L3 single photon data.

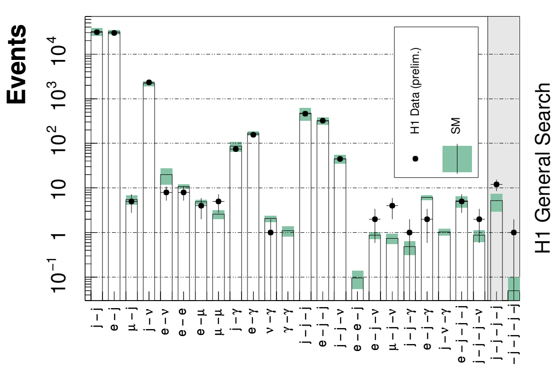

Figure 17. The number of observed and expected events for all event classes considered in the H1 general search for new phenomena.

the H1 analysis. In each channel, the part of the phase space where the data shows the largest deviation with the SM prediction is then identified, and the significance of this deviation is estimated using Monte Carlo experiments. In the H1 analysis, this procedure allows indeed to retrieve the "anomalies" reported in Secs. 2.4 and 2.5. No other significant deviation is observed by this analysis.

Such an approach is likely to be very helpful at the LHC experiments, where new physics might manifest itself in various final states. However such analyses require a very good understanding of the detectors and of the backgrounds, which will probably be achieved after some time of data taking.

6. Conclusions

Physics beyond the Standard Model is believed to possibly manifest itself at the TeV scale and many searches for new phenomena are carried out at the current experiments, some of which were presented in this non-exhaustive review. Although no convincing evidence for new physics has been observed so far, some "anomalies" remain to be clarified in the near future at the Tevatron and HERA colliders. Recent results coming from the Run II data at the Tevatron set the most stringent constraints on many models and the much larger luminosities expected within the next years will allow the TeV scale to be thoroughly probed.

Acknowledgments

I am very grateful to W. Addams, L. Bellagamba, M. Besançon, F. Boudjema, G. Broojmans, N. Castro, D. Dannheim, C. Diaconu, E. Gallo, F. Gianotti, G. Landsberg, N.S. Lockyer, C. Mariotti, H.U. Martyn, S. Mele, L. Poggioli, S. Rolli, A. Schöning, T. Sloan, I. Trigger, S. Worm, and A.F. Zarnecki for useful discussions or providing figures. I also thank the organizers for this very interesting symposium and the Scientific Secretaries for their help in preparing this talk.

References

1. M. Schmitt, these proceedings.
2. For a review, see A. Bellerive, these proceedings.
3. P. Gambino, these proceedings.
4. C.S. Wood *et al.*, *Science* **275**, 1759 (1997).
5. M. Kuchiev and V. Flambaum, hep-ph/0305053.
6. M. Davier *et al.*, *Eur. Phys. J.* C **27**, 497 (2003).
7. CMD-2 Collab., R.R. Akhmetshin *et al.*, hep-ex/0308008.
8. T. Browder, these proceedings.
9. CDF Collab., F. Abe *et al.*, *Phys. Rev.* D **59**, 092002 (1999).
10. CDF Collab., D. Acosta *et al.*, *Phys. Rev.* D **66**, 012004 (2002).
11. CDF Collab., D. Acosta *et al.*, *Phys. Rev.* D **65**, 052007 (2002); CDF Collab., G. Apollinari *et al.*, *Phys. Rev.* D **65**, 032004 (2002).
12. H1 Collab., A. Aktas *et al.*, DESY-03-082, to be published in *Eur. Phys. J.*
13. ZEUS Collab., "Study of multi-lepton production in $e^{\pm}p$ interactions at HERA", Contributed Paper. #910 to the ICHEP'02 Conference, Amsterdam (The Netherlands), July 2002.

14. H1 Collab., V. Andreev *et al.*, *Phys. Lett.* B **561**, 241 (2003).
15. ZEUS Collab., Contributed Paper. #909 to the ICHEP'02 Conference, Amsterdam (The Netherlands), July 2002.
16. T. Han, J. Hewett, *Phys. Rev.* D **60**, 074015 (1999).
17. H1 Collab., A. Aktas *et al.*, DESY-03-132, submitted to *Eur. Phys. J.*
18. ZEUS Collab., S. Chekanov *et al.*, *Phys. Lett.* B **559**, 153 (2003).
19. CDF Collab., *Phys. Rev. Lett.* **80**, 2525 (1998).
20. LEP Exotica Working Group, Note 2001-01.
21. CDF Collab., D. Acosta *et al.*, *Phys. Rev.* D **65**, 091120 (2002); D0 Collab., V.M. Abazov *et al.*, *Phys. Lett.* B **517**, 282 (2001).
22. E. Eichten, K. Lane and M. Peskin, *Phys. Rev. Lett.* **50**, 811 (1983).
23. H1 Collab., C. Adloff *et al.*, *Phys. Lett.* B **568**, 35 (2003); ZEUS Collab., "Search for large extra dimensions, finite quark radius and contact interactions in *ep* collisions at HERA", Contributed paper #602 to the EPS'01 Conference, Budapest (Hungary), July 2001.
24. K. Hagiwara, D. Zeppenfeld and S. Komamiya, *Zeit. Phys.* C **29**, 115 (1985).
25. F. Boudjema, A. Djouadi and J.L. Kneur, *Zeit. Phys.* C **57**, 425 (1993).
26. U. Baur, M. Spira and P.M. Zerwas, *Phys. Rev.* D **42**, 815 (1990).
27. DELPHI Collab., "Search for excited leptons with the DELPHI detector at LEP", Contributed Paper #291 to the ICHEP'02 Conference, Amsterdam (The Netherlands), July 2002; OPAL Collab., G. Abbiendi *et al.*, *Phys. Lett.* B **544**, 57 (2002).
28. LEP Exotica Working Group, Note 2001-02.
29. H1 Collab., C. Adloff *et al.*, *Phys. Lett.* B **548**, 35 (2002); ZEUS Collab., Contributed Paper #607 to the EPS'01 Conference, Budapest (Hungary), July 2001.
30. LEP II Diphoton WG, LEP2FF/02-02 (July 2002).
31. J. Bagger, C. Schmidt and S. King, *Phys. Rev.* D **37**, 1188 (1988); P.H. Frampton and S.L. Glashow, *Phys. Lett.* B **190**, 157 (1987); E.H. Simmons, *Phys. Rev.* D **55**, 1678 (1997).
32. W. Buchmüller, R. Rückl and D. Wyler, *Phys. Lett.* B **191**, 442 (1987); *Err. ibid* B **448**, 320 (1999).
33. ZEUS Collab., S. Chekanov *et al.*, *Phys. Rev.* D **68**, 052004 (2003).
34. H1 Collab., "A search for leptoquarks at HERA", Contributed Paper #185 to the LP'03 Symposium, Fermilab, August 2003; H1 Collab., C. Adloff *et al.*, *Phys. Lett.* B **523**, 234 (2001).
35. D0 Collab., B. Abbott *et al.*, *Phys. Rev. Lett.* **80**, 2051 (1998).
36. D0 Collab., *Phys. Rev. Lett.* **84**, 2088 (2000).
37. G.S. and R.N. Mohapatra, *Phys. Rev.* D **12**, 1502 (1975); R.N. Mohapatra and R.E. Marshak, *Phys. Rev. Lett.* **44**, 1316 (1980).
38. OPAL Collab., "Search for Doubly Charged Higgs Bosons with the OPAL detector at LEP", Contributed Paper #215 to the LP'03 Symposium, Fermilab, August 2003; DELPHI Collab., J. Abdallah *et al.*, *Phys. Lett.* B **552**, 127 (2003).
39. S. Godfrey, P. Kalyniak, and N. Romanenko, *Phys. Rev.* D **65**, 033009 (2002).
40. H1 Collab., "Search for doubly charged Higgs production at HERA", Contributed Paper #184 to the LP'03 Symposium, Fermilab, August 2003.
41. OPAL Collab., "Search for the Single Production of Doubly-Charged Higgs Bosons and Constraints on its Couplings from Bhabha Scattering", Contributed Paper #221 to the LP'03 Symposium.
42. L. Randall and R. Sundrum, *Phys. Rev. Lett.* **83**, 3370 (1999); idem, *Phys. Rev. Lett.* **83**, 4690 (1999).
43. T. Han, J.D. Lykken, R. Zhang, *Phys. Rev.* D **59**, 105006 (1999).
44. G.F. Giudice, R. Rattazzi and J.D. Wells, *Nucl. Phys.* B **595**, 250 (2001).
45. OPAL Collab., "Searches for Radions at LEP II", Contributed Paper #238 to the LP'03 Symposium, Fermilab, August 2003.
46. N. Arkani-Hamed, S. Dimopoulos and G. Dvali, *Phys. Lett.* B **429**, 263 (1998); I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali, *Phys. Lett.* B **436**, 257 (1998).
47. G.F. Giudice, R. Rattazzi and J.D. Wells, *Nucl. Phys.* B **544**, 3 (1999).
48. L3 Collab., "Single and Multi-Photon Events with Missing Energy in e^+e^- Collisions at $\sqrt{s} = 189 - 208$ GeV", L3 Note 2811, July 2003.
49. D0 Collab., V.M. Abazov *et al.*, *Phys. Rev. Lett.* **90**, 251802 (2003); CDF Collab., D. Acosta *et al.*, FERMILAB-PUB-03/285-E., submitted to *Phys. Rev. Lett.*, Sep. 2003.
50. J.L. Hewett, *Phys. Rev. Lett.* **82**, 4765 (1999).
51. K. Cheung and G. Landsberg, *Phys. Rev.* D **62**, 076003 (2000).
52. LEP Electroweak Working Group ($f\bar{f}$ subgroup), C. Geweniger *et al.*, LEP2FF/02-03 note.
53. D0 Collab., *Phys. Rev. Lett.* **86**, 1156 (2001).
54. A. Dobado and A.L. Maroto, *Nucl. Phys.* B **592**, 203 (2001); H. Murayama and J.D. Wells, *Phys. Rev.* D **65**, 056011 (2002).
55. L3 Collab., "Searches for Branons at LEP", Contributed Paper #829 to the EPS'03 Conference, Aachen (Germany), July 2003.
56. D0 Collab., *Phys. Rev.* D **64**, 012004 (2001).
57. H1 Collab., "General Search for New Phenomena in *ep* scattering at HERA", Contributed Paper #195 to the LP'03 Symposium, Fermilab, August 2003.

DISCUSSION

Peter Rosen (Department of Energy): Looking at like-sign dileptons, can you get better limits from nuclear double-beta decay?

Emmanuelle Perez: I was not aware of the answer at the time of the talk. This is what I found afterwards, going through the relevant literature.

With the standard gauge structure of the SM, the contribution of doubly-charged Higgses to the process $dd \to uue^-e^-$, via the trilinear interaction of H^{--} with the singly charged field belonging to the $SU(2)$ Higgs doublet, was first investigated by R.N. Mohapatra and J.D. Vergados in *Phys. Rev. Lett.* **47**, 1713 (1981). It was shown however that the corresponding amplitude is largely suppressed, being proportional to the square of the d quark mass (J. Schechter and J.W.F. Valle, *Phys. Rev.* D **25**, 2591 (1982); L. Wolfenstein, *Phys. Rev.* D **26**, 2507 (1982)). Schechter and Valle also showed that the contribution induced by $W^-W^- \to H^{--} \to e^-e^-$ is negligible as well, with a suppression proportional to the Majorana neutrino mass.

In left-right symmetric models the dominant contribution is induced by the H^{--} which belongs to the $SU(2)_R$ triplet, via its coupling to the right-handed W. However, as shown by M. Hirsch *et al.* in *Phys. Lett.* B **374**, 7 (1996), this contribution turns out to be numerically small unless the doubly-charged Higgs boson is very light.